The natural emergence of the SFR-H2 surface density relation in galaxy simulations

Alessandro Lupi
(Institut d’Astrophysique de Paris)

THE ROLE OF GAS IN GALAXY DYNAMICS

with: S. Bovino, P. R. Capelo, M. Volonteri, J. Silk

October 2nd, 2017
University of Malta
The observed KS relation

Bigiel+2008
H2-based star formation

**Standard prescription:**

\[
\dot{\rho}_{SF} = \varepsilon \frac{\rho_{gas}}{t_{ff}}
\]

\( (T_g < T_{g,\text{thr}}) \)

\( \rho_g > \rho_{g,\text{thr}} \)

**H2-based prescription:**

(Gnedin+09, Christensen+12, Hopkins+14, Tomassetti+15, Pallottini+17, Hopkins+17)

\[
\dot{\rho}_{SF} = \varepsilon_0 f_{\text{H}_2} \frac{\rho_{gas}}{t_{ff}}
\]

**BUT**

Recent theoretical studies have revealed a lack of causal connection between H\(_2\) and SF (Krumholz et al. 2011, Clark et al. 2012).

**MORE LIKELY**

The formation of H\(_2\) is controlled by SF, or, in general, by the gravitational collapse of atomic gas, not vice versa (Mac Low 2016).
Star formation model
(Turbulent magnetized clouds)

Padoan & Nordlund 2011

\[ p_s(s) = \frac{1}{\sqrt{2\pi\sigma_s^2}} \exp\left[ \frac{-(s - s_0)^2}{2\sigma_s^2} \right] \]

\[ \sigma_s^2 = \ln(1 + b^2\mathcal{M}^2) \]

The critical density for SF is related to the magnetic shock jump conditions and to the magnetic critical mass for collapse

\[ s_{\text{crit}} = \ln \left[ 0.067\theta^{-2}\alpha_{\text{vir}}\mathcal{M}^2 \right] \quad \alpha_{\text{vir}} = 5\sigma_v^2L/(6GM_{\text{cloud}}) \]

\[ \varepsilon = \frac{\epsilon_x}{2\phi_t} \exp\left( \frac{3}{8}\sigma_s^2 \right) \left[ 1 + \text{erf} \left( \frac{\sigma_s^2 - s_{\text{crit}}}{\sqrt{2\sigma_s^2}} \right) \right] \]

Federrath & Klessen 2012
Physically motivated SF
SN feedback + Mass losses from low-mass stars
Interstellar radiation field
Clumping factor
Evolved for 400 Myr in isolation

Galaxy with typical $z=3$ properties
NFW DM halo + exp. decay: $R_{\text{vir}} = 45$ kpc
$M_{\text{halo}} = 2 \times 10^{11} M_\odot$

Stellar + gaseous disc: $R_0 = 1.28$ kpc
$M_{\text{star}} = 1.6 \times 10^9 M_\odot$; $M_{\text{gas}} = 2.4 \times 10^9 M_\odot$

Hernquist stellar bulge: $a = 0.256$ kpc
$M_{\text{bulge}} = 8 \times 10^8 M_\odot$

Numerical setup
KROME
Non-eq. chemistry
(Photochemistry)

GIZMO
mesh-less
finite mass

GIZMO-KROME

GIZMO-KROME

GIZMO-KROME

October 2nd, 2017
University of Malta
The Interstellar radiation field

We implemented two sub-grid models and compared them with a full-RT simulation.

Model ‘S’

$$\tau = \frac{\sigma_{\text{eff}}}{m_H} \left( \rho_g R_{\text{max}} - |\nabla \rho_g| R_{\text{max}}^2/2 \right)$$

$$F = \sum_i \frac{L_{i,*}}{4\pi d_i^2} \exp(-\tau_i)$$

$$\tau = \sum_j \sigma_{j,\text{bin}} n_j \lambda \quad l_{\text{Sob}} = \frac{\rho_g}{|\nabla \rho_g|}$$
The Interstellar radiation field

Model ‘T’

\[ F = \left[ \sum_i \frac{L_{i,*}}{4\pi d_i^2} \exp(-\tau_i) \right] \exp(-\tau_g) \]

Around star:

\[ l_{\text{Sob}} = \frac{\rho_g}{|\nabla \rho_g|} \]

Around gas:

\[ \lambda_J = \frac{\sqrt{\pi} c_s}{\sqrt{G \rho}} \]
RT in GIZMO

Momentum method with M1 closure scheme
(Rosdahl et al. 2013)

\[
\frac{1}{c} \frac{\partial I_\nu}{\partial t} + \mathbf{n} \cdot \nabla I_\nu = S_\nu - k_\nu I_\nu
\]

\[
\begin{cases}
\frac{\partial N_\nu}{\partial t} + \nabla \cdot \mathbf{F}_\nu = N_\nu^* - k_\nu c N_\nu \\
\frac{\partial \mathbf{F}_\nu}{\partial t} + c^2 \nabla \cdot \mathbf{P}_\nu = -k_\nu c \mathbf{F}_\nu
\end{cases}
\]

Hopkins et al. (in preparation)
The clumping factor

\[ R_f(H_2) = 3 \times 10^{-17} n_{H_{tot}} n_{tot} Z/Z_\odot \text{ cm}^{-3} \text{s}^{-1} \]

PDF averaged rate

\[ \langle R_f(H_2) \rangle = 3 \times 10^{-17} \langle n_{H_{tot}} n_{tot} \rangle Z/Z_\odot \text{ cm}^{-3} \text{s}^{-1} \]

Express using average density

\[ \langle R_f(H_2) \rangle = 3 \times 10^{-17} \langle n_{H_{tot}} \rangle \langle n_{tot} \rangle C_\rho Z/Z_\odot \text{ cm}^{-3} \text{s}^{-1} \]

\[ C_\rho = \frac{\langle \rho^2 \rangle}{\langle \rho \rangle^2} = \exp(\sigma_s^2) = 1 + b^2 \mathcal{M}^2 \]
The effect of the interstellar radiation
The effect of the interstellar radiation
1) October 2nd, 2017

2) Formation of C\(^+\) in dwarf galaxies, using a more complete network including C, O an Si.

What’s next

\( Z_{\text{fin}} = 6 \)
\( M_{\text{vir}} \sim 2 \times 10^{12} \, M_\odot \)

\[
\begin{align*}
M_{\text{gas}} &= \sim 1.5 \times 10^4 \, M_\odot/\text{part} \\
M_{\text{DM}} &= \sim 8 \times 10^4 \, M_\odot/\text{part} \\
N_{\text{gas}} &= 6.75 \times 10^7 \\
N_{\text{DM}} &= 6.75 \times 10^7 \\
N_{\text{DM,low}} &= 2.2 \times 10^7 \\
\epsilon_{\text{gas,min}} &= 40 \, \text{cpc} \mid 2.5 \, \text{pc} \\
\epsilon_{\text{DM}} &= 640 \, \text{cpc} \mid 40 \, \text{pc} \\
\epsilon_{\text{star}} &= 192 \, \text{cpc} \mid 12 \, \text{pc}
\end{align*}
\]
Conclusions

Lupi et al. 2017 (submitted) - soon on ArXiv

We developed a new model to accurately track H₂ in numerical simulations using the package KROME, including photochemistry, SF, SNe, stellar radiation and shielding (gas, dust, H₂). We tested the model on an idealised setup of an isolated galaxy with typical properties of \( z=3 \) galaxies, assessing the effect of the different processes included.

- We found that the correlation between H₂ and SF surface densities can be naturally reproduced, if we account for all the most important processes and for a self-consistent clumping factor.

- We found that the correlation is also maintained at low H₂ surface densities.

- We concluded that an H₂-dependent SF prescription is not necessary and also unmotivated.
Thanks for your attention